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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

REPORT 960

DETERMINATION OF PLATE COMPRESSIVE STRENGTHS AT ELEVATED TEMPERATURES

By GEORGE J. HEIMERL and WILLIAM M. ROBERTS

1950

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AERONAUTIC SYMBOLS

1. FUNDAMENTAL AND DERIVED UNITS

	Symbol	Metric		English	
		Unit	Abbreviation	Unit	Abbreviation
Length	l	meter	m	foot (or mile)	ft (or mi)
Time	t	second	s	second (or hour)	sec (or hr)
Force	F	weight of 1 kilogram	kg	weight of 1 pound	lb
Power	P	horsepower (metric)		horsepower	hp
Speed	V	kilometers per hour	kph	miles per hour	mph
		meters per second	mps	feet per second	fps

2. GENERAL SYMBOLS

W Weight $=mg$

g Standard acceleration of gravity $=9.80665$ m/s² or 32.1740 ft/sec²

m Mass $=\frac{W}{g}$

I Moment of inertia $=mk^2$. (Indicate axis of radius of gyration k by proper subscript.)

μ Coefficient of viscosity

ν Kinematic viscosity

ρ Density (mass per unit volume)

Standard density of dry air, 0.12497 kg-m^{-4}-s^2 at 15° C and 760 mm; or 0.002378 lb-ft^{-4} sec^2

Specific weight of "standard" air, 1.2255 kg/m^3 or 0.07651 lb/cu ft

3. AERODYNAMIC SYMBOLS

S Area

S_w Area of wing

G Gap

b Span

c Chord

A Aspect ratio, $\frac{b^2}{S}$

V True air speed

q Dynamic pressure, $\frac{1}{2}\rho V^2$

L Lift, absolute coefficient $C_L=\frac{L}{qS}$

D Drag, absolute coefficient $C_D=\frac{D}{qS}$

D_0 Profile drag, absolute coefficient $C_{D_0}=\frac{D_0}{qS}$

D_i Induced drag, absolute coefficient $C_{D_i}=\frac{D_i}{qS}$

D_p Parasite drag, absolute coefficient $C_{D_p}=\frac{D_p}{qS}$

C Cross-wind force, absolute coefficient $C_C=\frac{C}{qS}$

i_w Angle of setting of wings (relative to thrust line)

i_t Angle of stabilizer setting (relative to thrust line)

Q Resultant moment

Ω Resultant angular velocity

R Reynolds number, $\rho\frac{Vl}{\mu}$ where l is a linear dimension (e.g., for an airfoil of 1.0 ft chord, 100 mph, standard pressure at 15° C, the corresponding Reynolds number is 935,400; or for an airfoil of 1.0 m chord, 100 mps, the corresponding Reynolds number is 6,865,000)

α Angle of attack

ϵ Angle of downwash

α_0 Angle of attack, infinite aspect ratio

α_i Angle of attack, induced

α_a Angle of attack, absolute (measured from zero-lift position)

γ Flight-path angle

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Langley Aeronautical Laboratory
Langley Air Force Base, Va.

National Advisory Committee for Aeronautics

Headquarters, 1724 F Street NW, Washington 25, D. C.

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REPORT 960

DETERMINATION OF PLATE COMPRESSIVE STRENGTHS AT ELEVATED TEMPERATURES

By George J. Heimerl and William M. Roberts

SUMMARY

The results of local-instability tests of **H**-*section plate assemblies and compressive stress-strain tests of extruded 75S–T6 aluminum alloy, obtained to determine flat-plate compressive strengths under stabilized elevated-temperature conditions, are given for temperatures up to 600° F. The results show that methods available for calculating the critical compressive stress at room temperature can also be used at elevated temperatures if the applicable compressive stress-strain curve for the material is given.*

INTRODUCTION

The strength of aircraft materials and structures at elevated temperatures is a question of increasing interest because of the trend toward high aircraft speeds at which aerodynamic heating (see reference 1) must be considered. At the present time, however, almost no information is available on the effects of elevated temperatures on the compressive strength of aircraft structural elements, such as columns or plates, or on the compressive properties of materials.

The results of a recent experimental investigation to determine the plate compressive strength of various aircraft structural materials at room temperature (see summary paper, reference 2) showed that the secant modulus, obtained from the compressive stress-strain curve for the material, could be used to calculate approximately the critical compressive stress of a plate. A more recent theoretical approach (reference 3) corroborated these results and provided a basis for a more accurate calculation of plate buckling by taking into account plate-edge conditions.

In order to ascertain whether methods adequate at room temperature for determining plate compressive strengths could be used at elevated temperatures, local-instability tests were made of extruded **H**-sections of 75S–T6 aluminum alloy at stabilized temperatures up to 600° F. This report presents the results of these tests and shows that the critical compressive stress at elevated temperatures may be determined from the applicable compressive stress-strain curve for the material.

METHODS OF TESTING AND ANALYSIS

Test specimens were made from three special **H**-section extrusions of 75S–T6 aluminum alloy having the cross section illustrated in figure 4 of reference 2. All tests were made in hydraulic-type testing machines accurate within three-fourths of 1 percent.

Compressive stress-strain tests.—The small furnace used in making the compressive stress-strain tests at elevated temperatures is shown in figure 1 together with the compression fixture and differential-transformer extensometer. The fixture utilized grooved plates for supporting a single-thickness specimen 2.52 inches long and 1.00 inch wide. General principles and the technique described in reference 4 were followed in regard to the design and operation of the fixture. An essential modification was a provision for mounting individual thermocouples at top, middle, and bottom positions on one of the side faces of the specimen.

The stress-strain tests were made under stabilized elevated-temperature conditions. Exposure times tended to vary at the beginning of the investigation from about 30 to 60 minutes because of the difficulty experienced at the higher temperatures in obtaining stabilized temperature conditions for short time exposures. After installation of ram heaters, satisfactory stabilized temperature conditions could readily

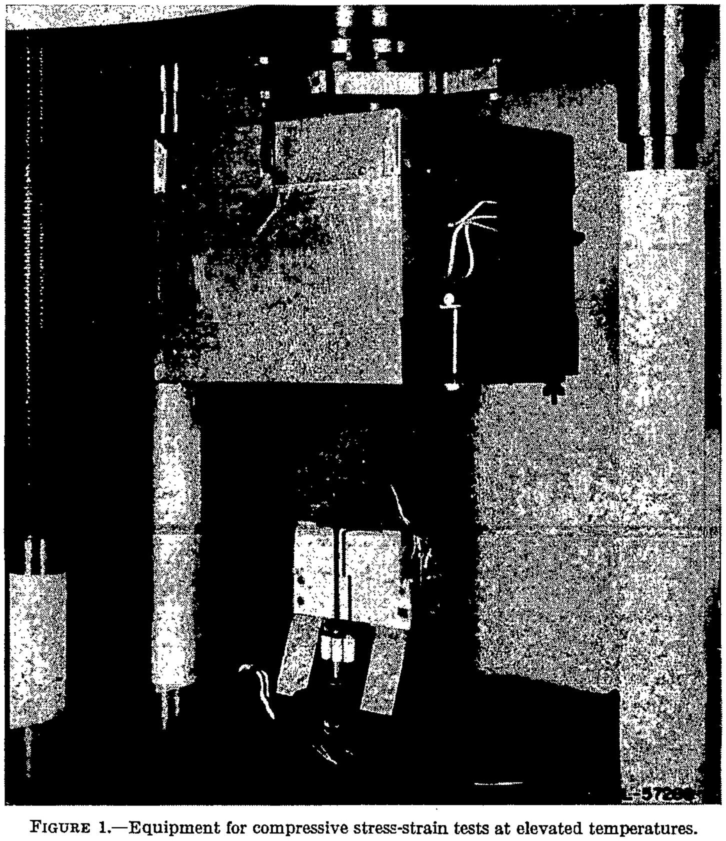

Figure 1.—Equipment for compressive stress-strain tests at elevated temperatures.

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be achieved in 40 minutes. Arbitrary strain rates of 0.002 and 0.004 per minute were used. In order to eliminate as much as possible the effects of lateral pressure from the supporting plates on the specimen, the support pressure was kept at a minimum. (See reference 4 for the technique in using compression fixtures.) The results of a few tests at 400° F in which the pressure was arbitrarily increased did not indicate any appreciable effects on either the compressive yield stress or the modulus of elasticity.

A special extensometer (see fig. 1) was required for measuring the strain over a 1-inch gage length on the specimen. A rod and tube assembly carried the relative movement of two sets of gage points below the furnace to two differential transformers, one of which can be seen in figure 1. Both load and strain were recorded autographically.

Voltage control of three horizontal banks of strip heaters in the furnace, and of both the top and bottom ram heaters, resulted in satisfactory temperature control. The maximum variation of temperature along the length of the specimen could be readily kept within 1° or 2° F. A controller, operated from a thermocouple on the fixture, was used for temperature control. Specimen, air, fixture, and ram temperatures were recorded.

Local-instability tests.—The plate compressive strength was determined from tests of extruded **H**-section plate assemblies so proportioned that the plate elements failed by local instability. The method of testing was similar to that described in reference 2 except for modifications necessary for tests at elevated temperatures.

The three-section furnace, designed to accommodate various lengths of specimens, is shown in figure 2, together with the temperature control and recording equipment. The large furnace section had three horizontal banks of strip heaters and each small unit had one bank. Proper temperature distribution was obtained through voltage control in each bank or set of banks of strip heaters as desired, as well as by individual control of the top and bottom ram heaters.

In order to detect buckling, the lateral displacement of the flange of the **H**-section was transferred to a differential-transformer gage below the furnace by means of a rigid-lever system (see fig. 3). Both the load and lateral displacement were recorded autographically. The local-instability tests were made under stabilized temperature conditions comparable to those used in making the compressive stress-strain tests and were made at the same strain rates of 0.002 and 0.004 per minute and an exposure time averaging about 40 minutes.

Analysis of the compressive properties.—Inasmuch as the compressive yield stress for extruded **H**-sections of 75S–T6 aluminum alloy tends to vary over the cross section (see fig. 3 of reference 2), a representative stress-strain curve applicable to the entire cross section is needed for correlation with the local-instability test results. The method used herein for obtaining a representative stress-strain curve for each

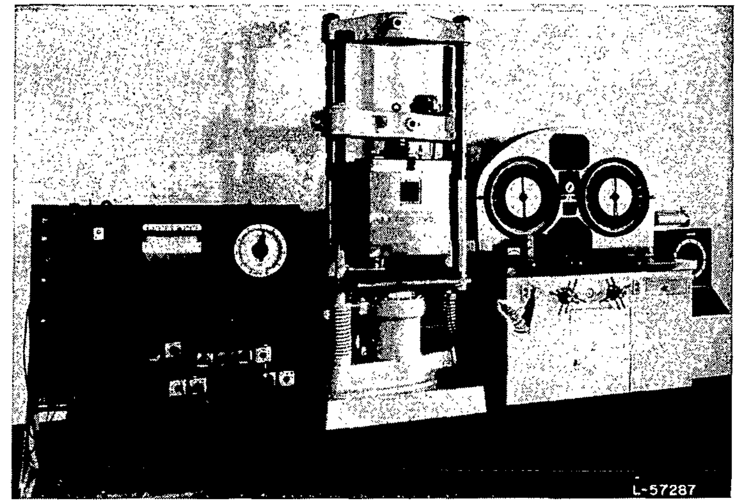

FIGURE 2.—Equipment for plate-buckling tests at elevated temperatures.

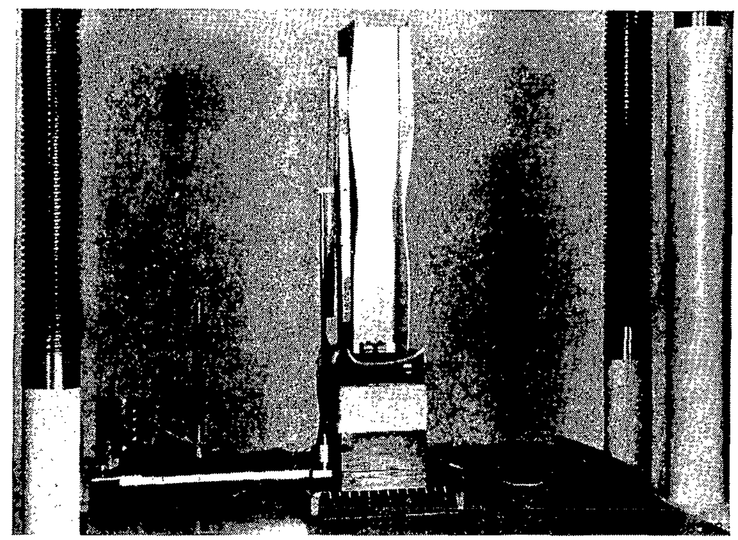

FIGURE 3.—Plate-buckling detection equipment.

extrusion is based on the assumptions that values of the compressive yield stress σ_{cy} (0.2 percent offset) for the flange and web material apply to the entire width of these respective elements and that a representative value for the cross section can be had by calculating an average from the values of σ_{cy} for the flange and web weighted by taking into account the areas of these elements. A representative stress-strain curve having this calculated value of σ_{cy} was then constructed from the available stress-strain curves for the extrusion. Average stress-strain curves for each temperature and strain rate were then determined from the representative curves for the three extrusions.

Analysis of local-instability tests.—At room temperature, the critical compressive stress σ_{cr} for **H**-section plate assemblies may be calculated from the modified plate-buckling equation

$$\sigma_{cr}=\frac{\epsilon k_W \pi^2 \eta E t_W^2}{12(1-\mu^2) b_W^2} \tag{1}$$

In equation (1), k_W is a nondimensional coefficient dependent upon plate proportions and edge conditions to be used with t_W and b_W the thickness and width of the web of the **H**-section (values of k_W are given in reference 5, and the method of dimensioning is shown in fig. 4 of reference 2), μ is Poisson's ratio, E is Young's modulus, and η is a coefficient which is a measure of the reduced plate modulus ηE. (For stresses in the elastic range, $\eta=1$; whereas, above the elastic range, $\eta<1$.)

As in reference 2, the local-instability test results are herein correlated with the compressive stress-strain curve by plotting the experimental values of σ_{cr} against the calculated elastic critical compressive strain ϵ_{cr} given by

$$\epsilon_{cr}=\frac{k_W\pi^2 t_W{}^2}{12(1-\mu^2)b_W{}^2} \tag{2}$$

Equation (2) is derived from equation (1) by setting $\eta=1$ and dividing both sides by E.

In the course of this investigation a consistent lack of correlation was found at elevated temperatures in the elastic range when μ was taken as 0.33, the room-temperature value for 75S–T6 aluminum alloy. When μ was arbitrarily increased with increasing temperatures, however, a satisfactory correlation was obtained in the elastic range. The assumed values of μ, referred to again in the section entitled "Results," were then used in equation (2). This procedure was necessary because no direct evaluation of the variation of μ with temperature was available.

RESULTS

The test results are summarized in table 1 and figures 4 to 9.

Compressive stress-strain tests.—Average compressive stress-strain curves, together with upper-limit and lower-limit representative curves for the three 75S–T6 aluminum-alloy **H**-section extrusions, are shown in figure 4 for strain rates of 0.002 and 0.004 per minute and at room temperature (RT), 200° F, 400° F, and 600° F. From these average curves, the variation of the secant modulus E_{sec} and tangent modulus E_{tan} with stress and temperature is shown in figure 5 for convenience in analyzing plasticity effects.

The ratio of the yield stress at a given temperature to that at room temperature for both the compressive yield stress σ_{cy} and the tensile yield stress σ_{ty} is plotted against temperature in figure 6. Data for σ_{ty} were taken from reference 6. The fact that the ratio for σ_{cy} varies with temperature in about the same manner as that for σ_{ty} suggests that values of σ_{cy} at elevated temperatures may possibly be estimated from the more frequently available data for σ_{ty} at elevated temperatures.

The variations of Young's modulus E and Poisson's ratio μ with temperature are shown in figure 7. Values of μ shown were obtained indirectly as mentioned previously and, while they appear reasonable, should be regarded only as approximate. For comparative purposes, the variation of E with temperature obtained from tensile tests of a number of cast aluminum alloys (reference 7) is also shown in figure 7. Here the lack of agreement between the results in tension and compression is marked. Differences between such results for cast and extruded aluminum alloys, however, are probably to be expected.

In order to show the effect of different time exposures at a given temperature, a few tests were made for exposure times ranging from ½ hour to 2 hours at 400° F (see fig. 8).

TABLE 1

LOCAL-INSTABILITY TEST RESULTS FOR EXTRUDED 75S–T6 ALUMINUM-ALLOY **H**-SECTIONS

Column	Temperature, T (° F)	Strain rate (per min)	Exposure time (min)	Poisson's ratio, μ (assumed)	ϵ_{cr} [a]	σ_{cr} (ksi)	$\bar{\sigma}_{max}$ (ksi)	$\sigma_{cr}/\bar{\sigma}_{max}$	σ_{cy} (ksi) [b]	σ_{cr}/σ_{cy}
1	201	0.002	33	0.33	0.00213	21,410	44,250	0.484	73,000	0.294
2	205	.004	40	.33	.00213	21,600	44,800	.481	73,800	.292
3	200	.002	40	.33	.00364	36,650	50,000	.734	71,300	.514
4	202	.004	37	.33	.00361	37,250	50,200	.742	70,600	.527
5	200	.002	40	.33	.00617	60,200	61,200	.983	74,200	.812
6	201	.004	33	.33	.00610	60,400	61,400	.983	74,200	.814
7	200	.002	35	.33	.00975	71,400	72,300	.987	74,200	.962
8	198	.004	35	.33	.00969	71,900	72,900	.987	74,200	.968
9	400	.002	45	.40	.00226	18,500	25,700	.720	41,900	.442
10	400	.004	40	.40	.00226	18,700	27,600	.678	43,300	.432
11	407	.002	60	.40	.00386	30,700	31,700	.969	39,900	.770
12	405	.004	35	.40	.00385	31,100	33,300	.935	43,800	.710
13	400	.002	50	.40	.00652	39,900	40,800	.978	43,000	.928
14	399	.004	40	.40	.00652	41,700	42,200	.988	43,100	.966
15	404	.002	35	.40	.00817	40,250	41,100	.978	43,000	.935
16	405	.004	34	.40	.00820	42,900	43,300	.990	43,100	.994
17	611	.002	72	.47	.00237	5,360	5,450	.983	6,650	.806
18	604	.004	60	.47	.00237	6,160	6,270	.982	7,080	.872
19	595	.002	52	.47	.00391	6,390	6,480	.985	6,750	.945
20	600	.004	54	.47	.00405	6,820	6,960	.980	7,370	.925
21	599	.002	60	.47	.00407	6,580	6,670	.986	6,750	.975
22	600	.004	58	.47	.00408	6,940	7,340	.945	7,370	.940
23	603	.002	55	.47	.00417	6,240	6,390	.977	6,750	.924
24	599	.004	54	.47	.00115	7,210	7,220	.998	7,370	.978
25	604	.002	60	.47	.00701	6,680	6,880	.972	6,430	1.040
26	602	.004	60	.47	.00704	7,310	7,580	.955	7,080	1.032
27	600	.002	50	.47	.00710	6,760	6,920	.977	6,430	1.051
28	597	.004	54	.47	.00710	7,470	7,620	.982	7,080	1.055

[a] $\epsilon_{cr}=\frac{k_W\pi^2 t_W{}^2}{12(1-\mu^2)b_W{}^2}$.

[b] Representative value.

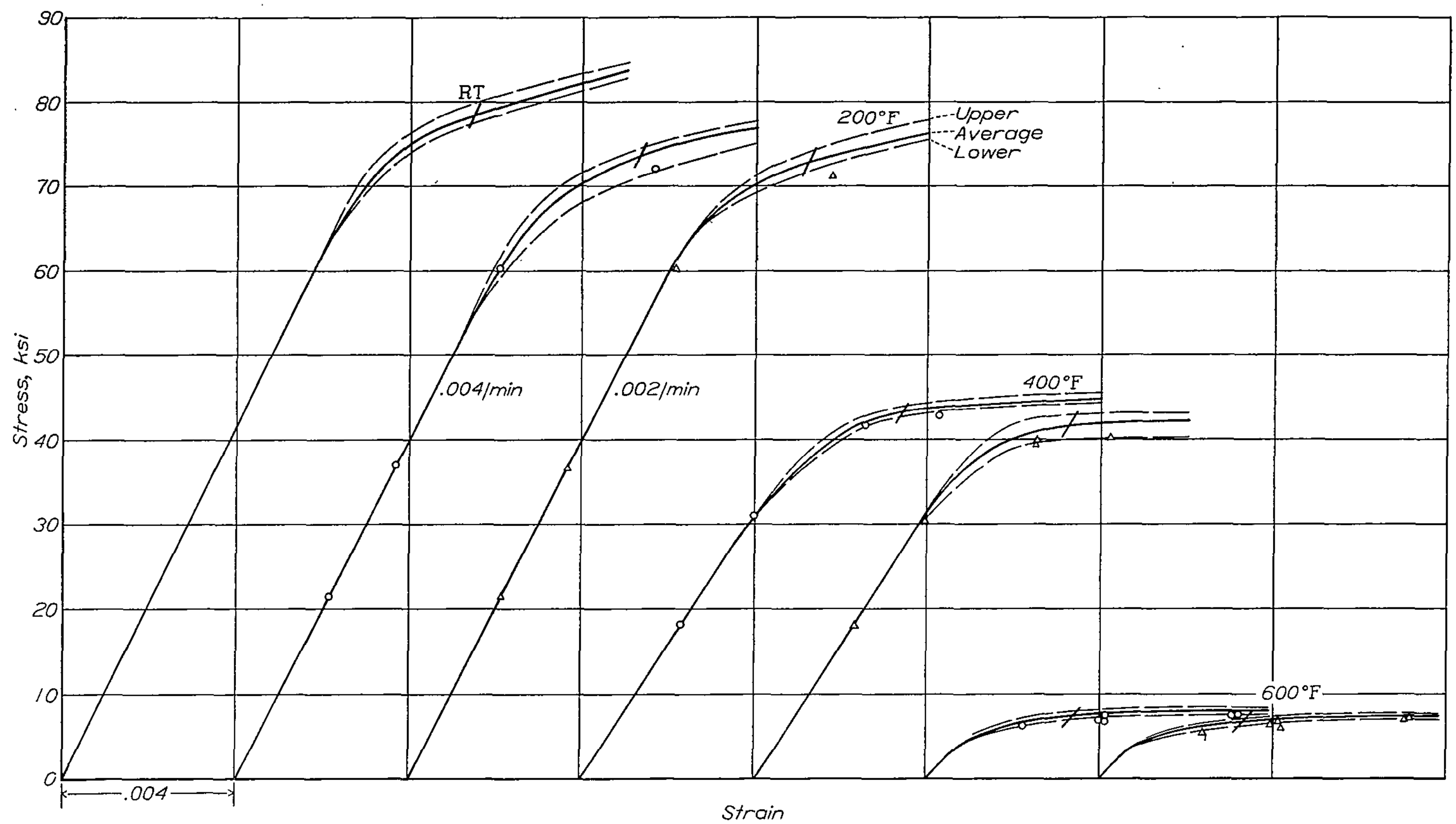

FIGURE 4.—Correlation of plate-compressive-buckling-test results with average compressive stress-strain curves for extruded 75S–T6 aluminum-alloy H-sections at elevated temperatures. (For plate tests, critical compressive stress is plotted against calculated elastic critical compressive strain.)

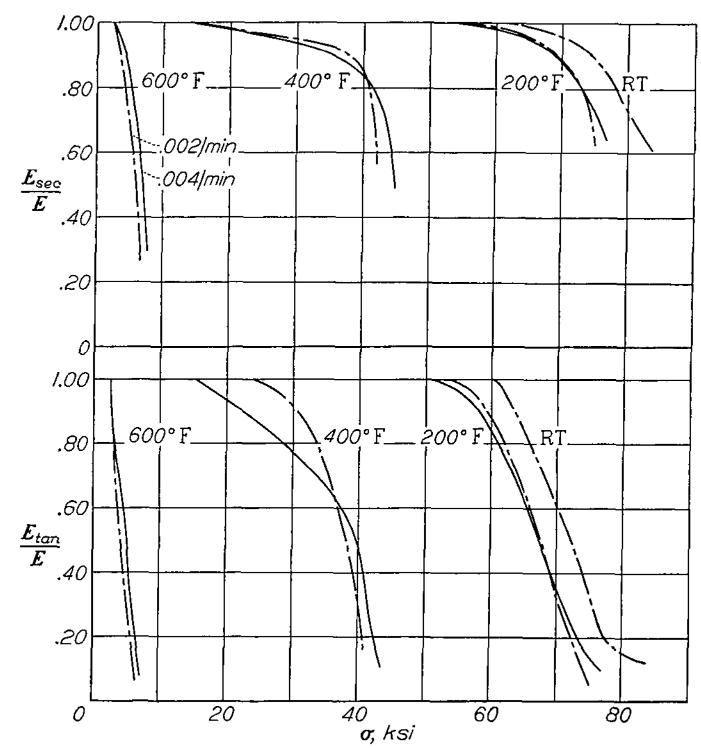

FIGURE 5.—Variation of the secant and tangent moduli with stress σ for the average stress-strain curves of figure 4 for elevated temperatures.

For the average exposure time for all the tests (40 min), a fairly rapid change of σ_{cy} is indicated at 400° F. At other temperatures, however, the effect of variation in exposure time is probably somewhat less (see fig. 5-13 of reference 6).

Local-instability tests.—The correlation of the critical compressive stress σ_{cr} (when plotted against the calculated elastic critical compressive strain ϵ_{cr}, equation (2)) with the average compressive stress-strain curves is shown in figure 4 for 200° F, 400° F, and 600° F. At elevated temperatures, good agreement is indicated for σ_{cr} in the elastic range; but in the plastic range, σ_{cr} tends to fall slightly below the stress-strain curves as was the case at room temperatures for 75S–T6 aluminum alloy as well as other materials (see fig. 5 of reference 2). The effective modulus ηE is therefore only slightly less than the secant modulus which would apply if the data would plot exactly along the stress-strain curve.

The same relationship exists between σ_{cr}, the average stress at maximum load $\bar{\sigma}_{max}$, and the compressive yield stress σ_{cy} at elevated temperatures as existed at room temperature (see fig. 9). For stresses greater than about $\frac{3}{4}\sigma_{cy}$, values of $\bar{\sigma}_{max}$ are only slightly greater than σ_{cr}; but for stresses less than about $\frac{3}{4}\sigma_{cy}$, values of $\bar{\sigma}_{max}$ become appreciably greater than σ_{cr} as σ_{cr} is reduced.

For a given value of ϵ_{cr}, the values of σ_{cr} and $\bar{\sigma}_{max}$ are somewhat greater for the higher strain rate (0.004 per min) than for the lower (0.002 per min), although the effect of the variation in strain rate was not appreciable for these low strain rates except perhaps at 400° F (see figs. 4 and 9). The increase in σ_{cr} with strain rates corresponds approximately to the increase in stress obtained for the corresponding compressive stress-strain curves (see fig. 4).

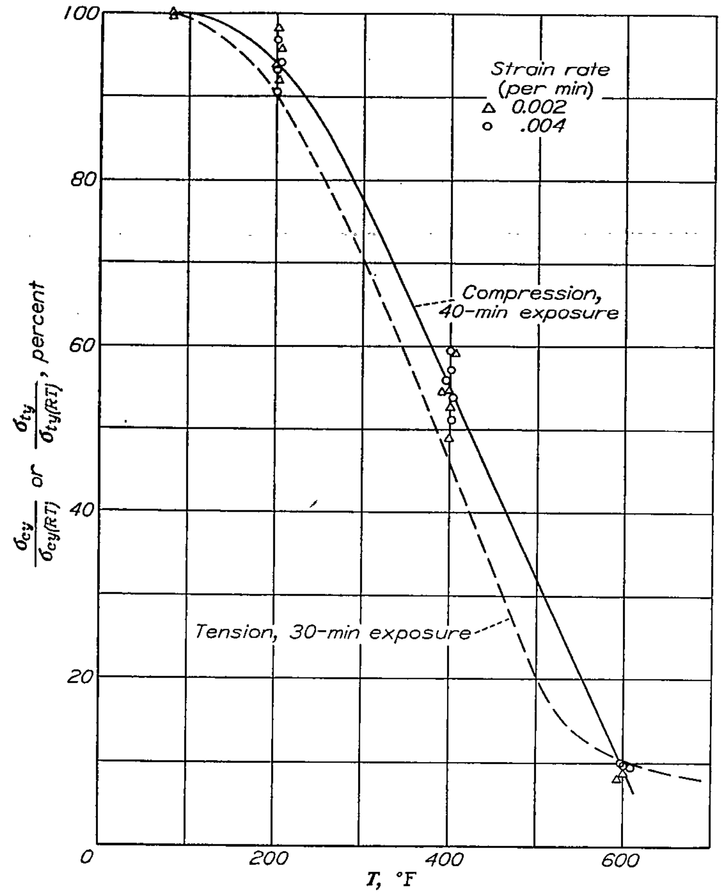

FIGURE 6.—Variation of the compressive yield stress σ_{cy} and tensile yield stress σ_{ty} with temperature T for extruded 75S-T6 aluminum alloy. (Data for tension from reference 6.)

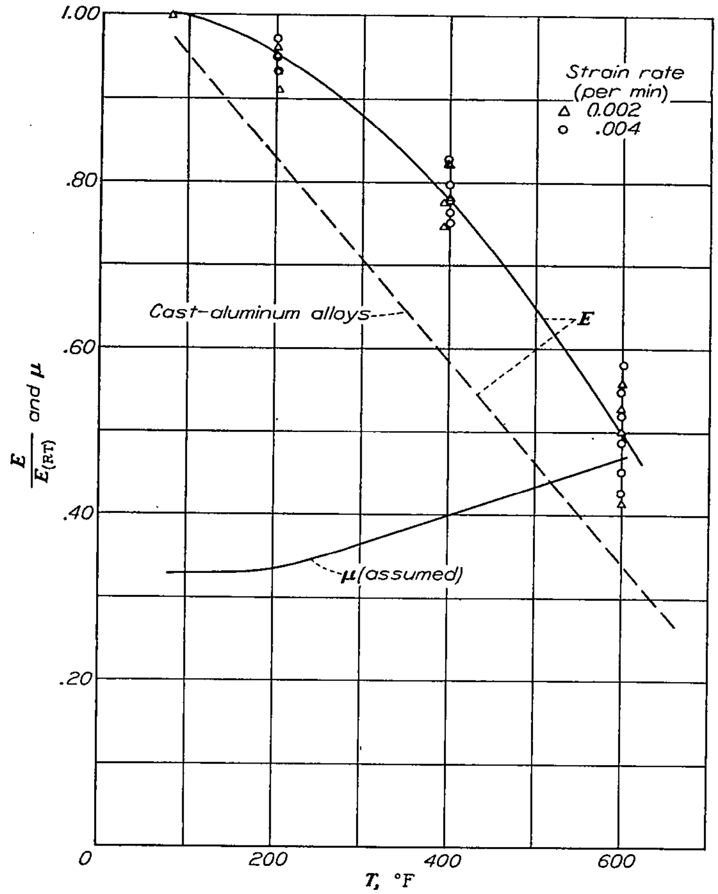

FIGURE 7.—Variation of Young's modulus E and Poisson's ratio μ with temperature for extruded 75S-T6 aluminum alloy. (Data for cast-aluminum alloys from reference 7.)

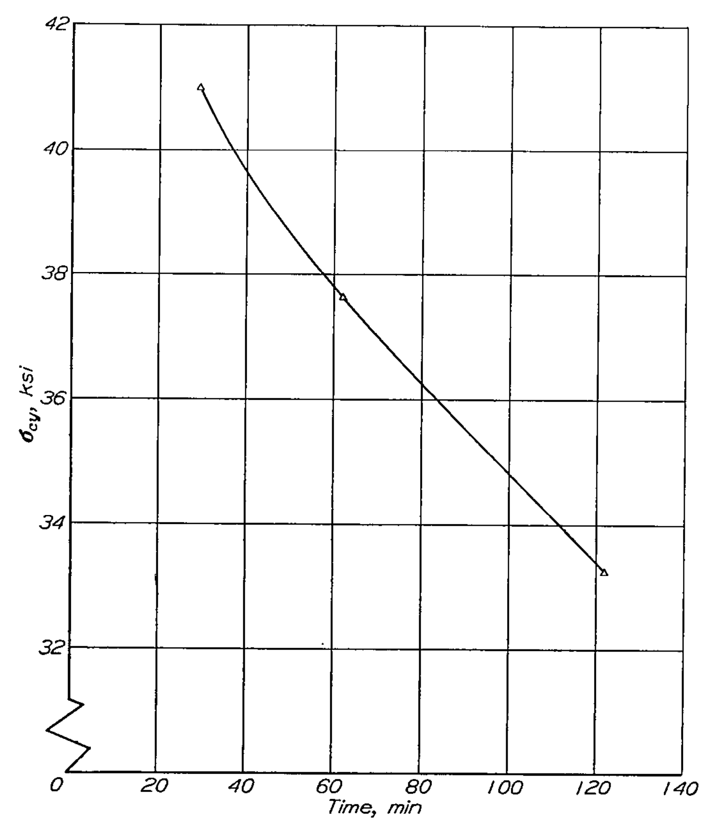

FIGURE 8.—Effect of variation of exposure time at 400° F on the compressive yield stress σ_{cy} for extruded 75S-T6 aluminum alloy. (Values of σ_{cy} shown are the average for one cross section at a strain rate of 0.002/min.)

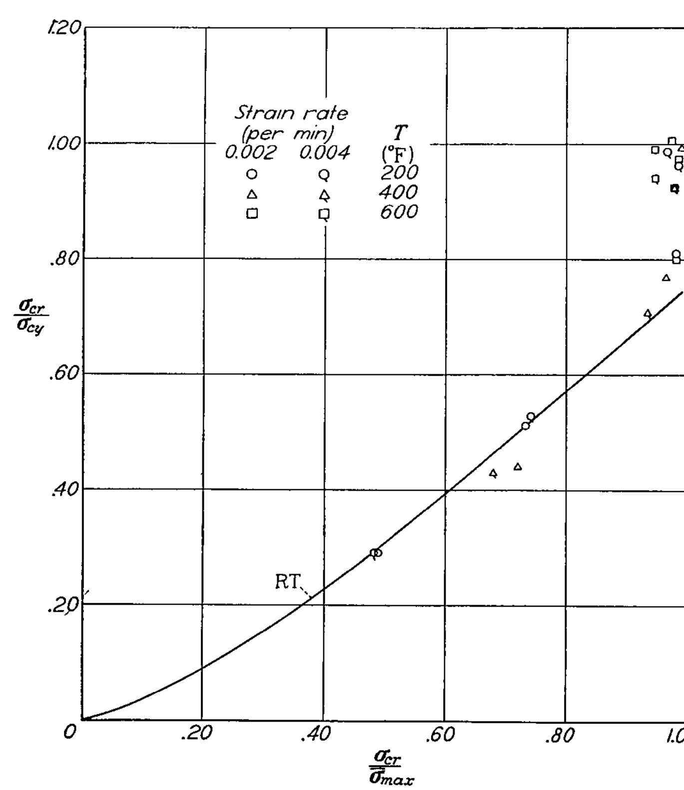

FIGURE 9.—Experimental relation between the critical compressive stress σ_{cr}, the average stress at maximum load $\bar{\sigma}_{max}$, and the compressive yield stress σ_{cy} for extruded 75S-T6 aluminum alloy H-sections at elevated temperatures. (Data for room temperature from reference 2.)

CONCLUSIONS

The results of the local-instability tests of extruded **H**-sections of 75S–T6 aluminum alloy warrant the following conclusions regarding the determination of compressive strengths of flat plates or plate assemblies of various materials at elevated temperatures:

1. The critical compressive stress σ_{cr} for **H**-section plate assemblies of extruded 75S–T6 aluminum alloy may be determined approximately at elevated temperatures as well as at room temperature by the use of the compressive stress-strain curve for the material for the desired temperature, strain rate, and exposure time. At elevated temperatures, the secant-modulus method is slightly unconservative in the plastic region as was found to be the case at room temperature for this material.

2. Approximately the same relationship exists between σ_{cr}, the average stress at maximum load $\bar{\sigma}_{max}$, and the compressive yield stress σ_{cy} at elevated temperatures as at room temperature for **H**-section plate assemblies. For σ_{cr} above $\frac{3}{4}\sigma_{cy}$, values of $\bar{\sigma}_{max}$ are only slightly greater than σ_{cr}; whereas, for σ_{cr} below $\frac{3}{4}\sigma_{cy}$, values of $\bar{\sigma}_{max}$ may be appreciably greater than σ_{cr}.

3. In view of the consistent general relationship previously found at room temperature between the **H**-section plate-assembly test results for the critical compressive stress σ_{cr} and the compressive stress-strain curve for a number of materials, and the fact that this relationship now appears to be valid at elevated as well as at room temperatures, it is reasonable to expect that σ_{cr} may be approximately determined at elevated temperatures for individual plates and various plate assemblies by methods which are satisfactory at room temperatures, provided that the compressive stress-strain curve for the material at the desired temperature, strain rate, and exposure time is given.

LANGLEY AERONAUTICAL LABORATORY,
NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS,
LANGLEY AIR FORCE BASE, VA., *December 6, 1948.*

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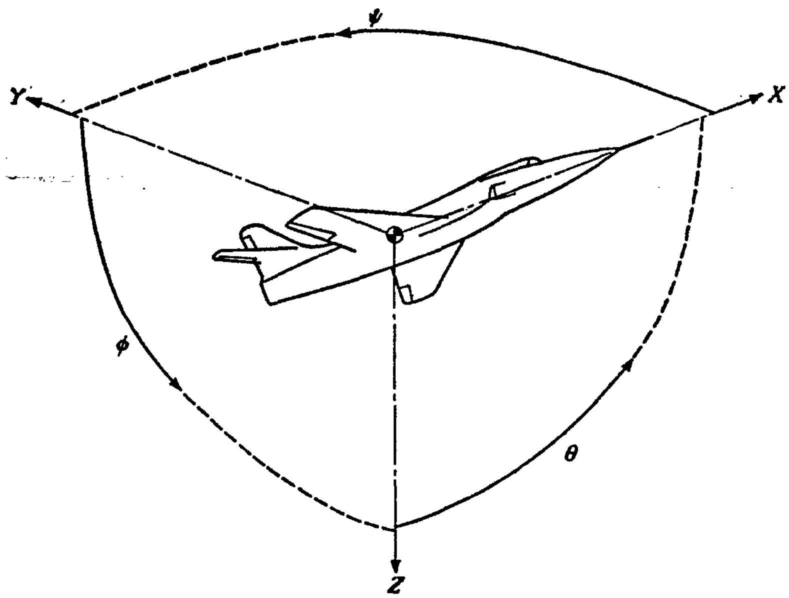

Positive directions of axes and angles (forces and moments) are shown by arrows

Axis		Force (parallel to axis) symbol	Moment about axis			Angle		Velocities	
Designation	Symbol		Designation	Symbol	Positive direction	Designation	Symbol	Linear (component along axis)	Angular
Longitudinal	X	X	Rolling	L	$Y \longrightarrow Z$	Roll	ϕ	u	p
Lateral	Y	Y	Pitching	M	$Z \longrightarrow X$	Pitch	θ	v	q
Normal	Z	Z	Yawing	N	$X \longrightarrow Y$	Yaw	ψ	w	r

Absolute coefficients of moment

$C_l=\frac{L}{qbS}$ (rolling) $\quad C_m=\frac{M}{qcS}$ (pitching) $\quad C_n=\frac{N}{qbS}$ (yawing)

Angle of set of control surface (relative to neutral position), δ. (Indicate surface by proper subscript.)

4. PROPELLER SYMBOLS

D	Diameter
p	Geometric pitch
p/D	Pitch ratio
V'	Inflow velocity
V_s	Slipstream velocity
T	Thrust, absolute coefficient $C_T=\frac{T}{\rho n^2 D^4}$
Q	Torque, absolute coefficient $C_Q=\frac{Q}{\rho n^2 D^5}$
P	Power, absolute coefficient $C_P=\frac{P}{\rho n^3 D^5}$
C_s	Speed-power coefficient$=\sqrt[5]{\frac{\rho V^5}{Pn^2}}$
η	Efficiency
n	Revolutions per second, rps
Φ	Effective helix angle$=\tan^{-1}\left(\frac{V}{2\pi rn}\right)$

5. NUMERICAL RELATIONS

1 hp=76.04 kg-m/s=550 ft-lb/sec
1 metric horsepower=0.9863 hp
1 mph=0.4470 mps
1 mps=2.2369 mph
1 lb=0.4536 kg
1 kg=2.2046 lb
1 mi=1,609.35 m=5,280 ft
1 m=3.2808 ft